Ion Heating and Fluctuations in the H-1NF Heliac

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Abstract. The H-1 heliac is being developed as a national research facility. A new power supply system which allows operation to fields ≤ 1 T has been commissioned; the ripple in the supply is controlled to < 0.01% to eliminate induced currents. Up to 100 kW of rf power at 7 MHz is used at present to produce plasmas using helicon waves. Multiple diagnostic studies of these plasmas and comparison experiments with a linear helicon device suggest that the near fields of the rf antennas result in ion temperatures that increase at the edge of the plasma, even though the antennas are 3-4 cm outside the last closed flux surface. Probe and spectroscopic results indicate that there the mass flow velocities are much less than the $\mathbf{E} \times \mathbf{B}$ velocity. Thus, radial force balance holds in detail, and the ambipolar radial electric field balances the ion pressure gradient. In L-mode plasmas, tomographic interferometry and probe studies show low-mode-number coherent oscillations in electron density and electron and ion temperatures that are suppressed at the L-H transition.

1. Introduction

The H-1NF heliac [1] is a medium-sized helical axis stellarator experiment with major radius $R = 1$ m, average plasma minor radius $a = 0.15$–0.2 m. Its “flexible-heliac” [2] coil set permits extraordinary variation in the low-shear rotational transform profile in the range $0.6 < \bar{\iota} < 2.0$ and variable average magnetic well. The ultimate design ratings of the H-1 facility are toroidal magnetic field $B = 1$ T and heating power P ≈ 500 kW, but early experiments have been limited to $B = 0.2$ T and P = 100 kW of 7 MHz helicon wave heating [3]. A new 12 MW power supply with very low current ripple (< 1 A ripple on 14 kA one-second flat-top current) has been commissioned, and work is underway to bring a 250 kW, 4-26 MHz transmitter and 200 kW, 28 GHz gyrotron into plasma operation.

Low-field, low-power operation on H-1NF in argon and helium has been used to explore the physics of an L-H like transition in which a sudden increase in density and density gradient is accompanied by changes in the radial electric field, the suppression of turbulence, improved particle confinement, and an increase in ion temperature. This paper describes recent experiments exploring the behaviour of the ions in these low-field discharges and characterisation of the fluctuations in L-mode plasmas.

2. Ion temperature profiles with rf heating

The plasma in H-1NF is heated using up to 100 kW of power at 7 MHz. Fig. 1 shows the arrangement of the antenna and flux surfaces. The picture frame antenna is located 3-4 cm outside the last closed flux surface, and so is not functioning as a limiter. Fig. 2 shows typical time traces of the plasma density obtained in this mode of operation—after an initial low-density phase, a transition to high confinement occurs. A key feature of these H-1NF plasmas is that

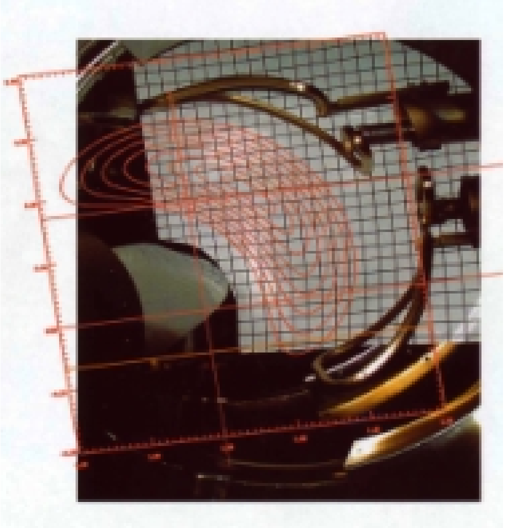

Fig. 1. Tangential view of saddle antenna in H-1NF, with plots of typical flux surface geometry superimposed. Reference grid size is 2 cm/square.

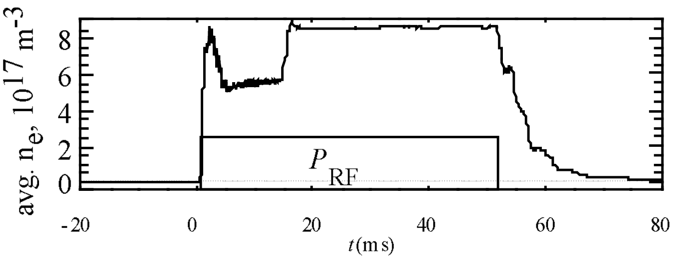

Fig. 2. Density time trace for typical H-1NF discharge.

there is no external momentum input, and spectroscopic and probe studies show that the plasma flow is at least 10× less than the **E** × **B** velocity [4].

Ion energies in these plasmas are measured using a retarding field energy analyser (RFEA) [4] which can be inserted inside the plasma because of its relatively low density.

Figure 3 shows profiles of density and electron temperature (measured with triple Langmuir probes) together with measurements of apparent ion temperature determined with the RFEA. The RFEA T_i profile appears roughly uniform with radius, falling somewhat at the edge.

In contrast, measurements of ion temperatures in argon plasmas using a novel electro-optic Fourier-transform imaging spectrometer, the MOSS (modulated solid-state spectrometer), show evidence of a hollow ion temperature profile [6]. The two profile shapes can be reconciled if we use information from probe measurements of the radial electric field to adjust the T_i profile measured near the axis with the RFEA to enforce the radial force balance condition in the absence of flow, ie:

$$E_r = \nabla p_i / (Z e n_e) \tag{1}$$

Figure 4 shows the comparison of the E_r profile with the RHS of Eq. (1), where experimental electric field and density profiles have been used, and the ion temperature profile has been adjusted. This procedure results in the hollow T_i profile shown in Fig. 3, which is in qualitative agreement with the spectroscopic measurements.

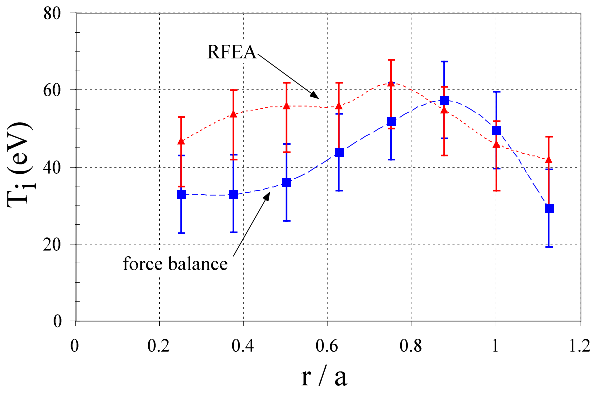

Fig. 3. Profile of ion temperature measured with the RFEA, and as adjusted to satisfy radial force balance.

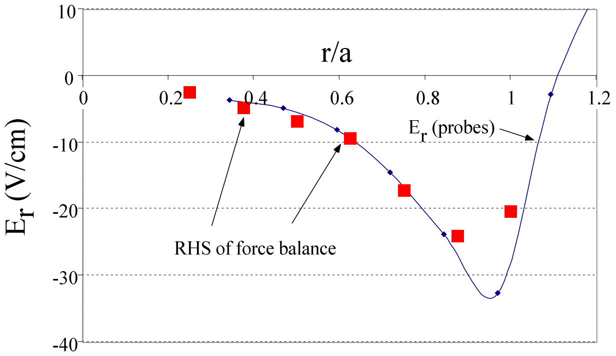

Fig. 4. Comparison of measured profile of radial electric field with RHS of Eq. (1); T_i *has been constrained so that radial force balance holds, resulting in the hollow profile shown in Fig. 3.*

The details of the RFEA current-voltage characteristics also suggest that the ion temperatures in the center of the discharge might be lower; Fig. 5 shows one such characteristic, in which there is evidence of both a low-energy and high-energy component.

3. Comparison with results from a low-field linear helicon device

To better understand the ion energy behaviour as measured by the RFEA, we have carried out model experiments [6] in a linear helicon plasma machine heated with up to 800 W of low-frequency power at low magnetic field. Typical ion energy distribution functions (IEDFs) are shown in Fig. 6. Measurements close to the source show a double-humped distribution, while measurements further from the source show a peaked distribution. Comparisons with theoretical modeling shows that depending on the relationship between the ion transit time and the rf period, the rf modulation can distort the IEDF in this way.

Examination of the RFEA characteristics for rf heated discharges in H-1NF reveals that in the inner region of the discharge, there is evidence of double-humped IEDFs similar to those seen in the linear device experiments. These observations lend further support to our conclusion that the ion temperatures profiles in H-1NF are hollow. This suggests that the ion heating observed in H-1NF at low densities is connected to acceleration in the sheath field of the antenna.

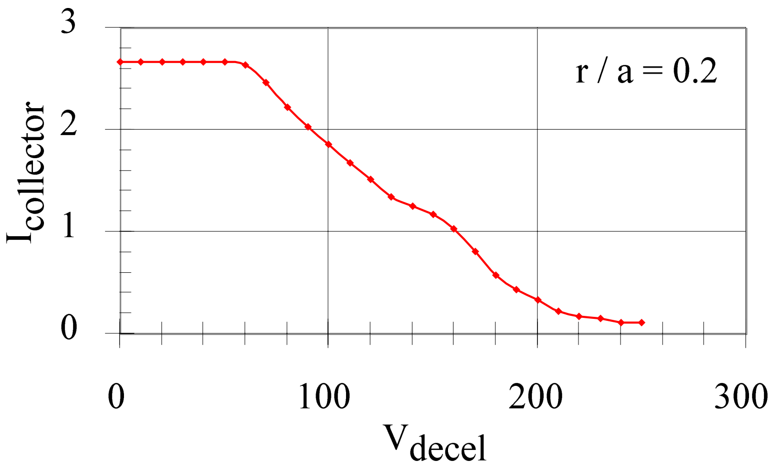

Fig. 5. RFEA chatacteristic for the central region of an H-1NF discharge.

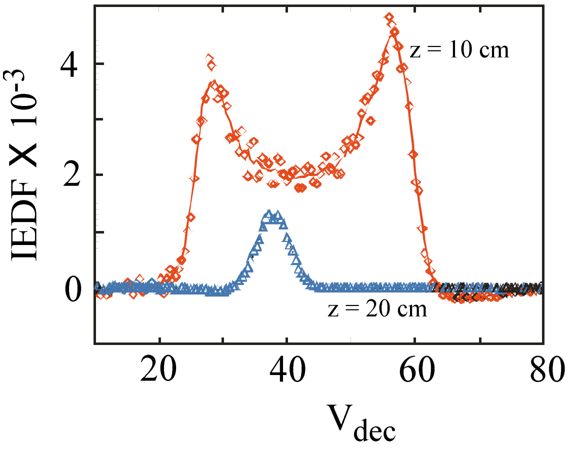

Fig. 6. Ion energy distributions determined using a retarding-field energy analyser in the linear helicon device. The upper curve is measured close to the source, the lower curve further downstream.

4. Fluctuation studies

L-mode plasmas in H-1NF exhibit strong fluctuations. We have developed a composite triple-probe/radial Mach-probe/triple probe (TMT probe) and an associated iterative technique which allows measurements of probe potentials and saturation currents to be combined to produce computed signals for the fluctuating density and electron and ion temperatures. In the first instance, this analysis assumes the fluctuation-induced particle flux is ambipolar. Application of this technique to sample L-mode discharges yields derived signals with

$$\tilde{n} / n \approx \tilde{T}_e / T_e \approx \tilde{T}_i / T_i \approx 30\% \tag{2}$$

A further set of two triple probes has now been added in a different toroidal location; addition of data from the new probes to the analysis scheme will permit an experimental study of Poisson’s equation to determine whether the fluctuation-induced flux is indeed ambipolar.

We have also imaged fluctuations in H-1NF using a tomographic FIR interferometer in which a rotating grating provides multiple views of the plasma. Figure 7 shows reconstructions of density contours at several points in an instability cycle in an L-mode plasma.

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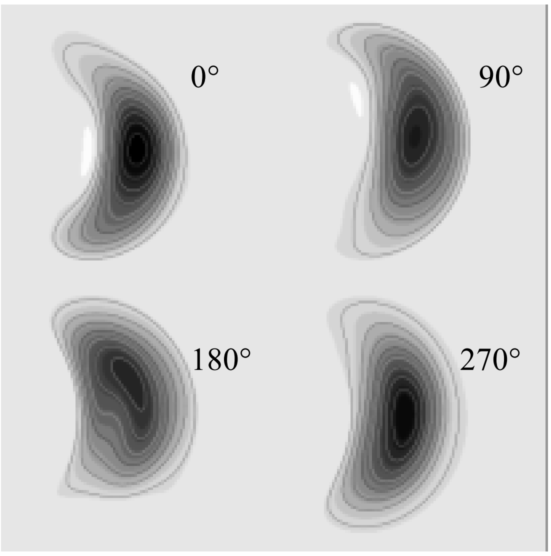

Fig. 7. Reconstructed plasma electron density profile for a fluctuating L-mode in H-1NF. The fundamental frequency of the mode is 1.9 kHz, and contours are shown for four phases. The plasma was produced in the standard magnetic configuration of H-1NF with 60 kW of 7 MHz helicon wave RF power.

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